JPL D-11383

NASA Unmanned Flight Anomaly Report

ANALYSIS OF UPLINK/DOWNLINK ANOMALIES ON SIX JPL SPACECRAFT

September 1994

National Aeronautics and
Space Administration

JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ABSTRACT

NASA Unmanned Flight Anomaly Reports

The NASA Unmanned Flight Anomaly Reports present the results of a series of analyses of in-flight hardware anomalies which have occurred on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. All of these analyses are funded by NASA Code QT under Research Technology Operation Plan (RTOP) 623-63-03, entitled *Flight Anomaly Characterization*. The objective of these analyses is to search for meaningful characterizations of in-flight anomaly data including any trends, patterns, or similarities that can be exploited to improve Product Assurance Program processes, ultimately leading to reduced numbers of anomalies on future unmanned flight programs.

This report addresses in-flight, hardware anomalies that have affected the uplink or downlink process, including science data, on six JPL spacecraft: Viking 1 and 2, Voyager 1 and 2, Magellan and Galileo. All of these programs were Class A missions as now defined by JPL D-1489, *Flight Equipment Classifications and Product Assurance Requirements*. An important finding of the analysis was that all of the spacecraft studied, except Viking 1 would have experienced a major failure of the uplink or downlink process if there had not been functional redundancy on board the spacecraft. This finding has significance for Product Assurance programs on future systems. The implication is that some subsystem redundancy is essential to successful interplanetary missions. A chart was developed, based on the JPL data, showing expected probability of success as a function of flight time for single-string spacecraft which may be useful for new spacecraft designs. The frequency of serious anomalies on previous Class A missions strongly suggests that this conclusion be applied to non-Class A missions as well.

The data also suggests that the analysis performed when ground test failures occurred has been generally successful in predicting flight performance and preventing catastrophic failures, even though in-flight failures did occur. This issue becomes much more critical for the expected single-string missions of the future, but the results indicate that it can be done, given full understanding of the underlying "physics of failure" and a willingness to take the programmatic steps which that understanding dictates.

For further information on the content of this report, contact Arthur Brown at (818) 542-6950. For additional copies of this document, contact the JPL Document Vellum Files at extension 4-5004.

JPL D-11383 **September 1994**

SUBJECT: Analysis of Uplink/Downlink Anomalies on Six JPL Spacecraft

SUMMARY

This report presents the results of an analysis of in-flight anomalies related to the uplink and downlink process on six JPL spacecraft. In addition to telecommunications link failures, failures that caused a loss of critical data were also considered. Eighteen of a total of 82 anomalies were related to the uplink and/or downlink process in some way. An important finding of the analysis was that a significant degradation or failure of the uplink/downlink process would have occurred on every JPL mission, except Viking 1, had it not been for functional redundancy. Sometimes, this redundancy was provided within the Radio Frequency Subsystem (RFS) and at other times by or within other subsystems such as gyros or reserve memory. This result has significance for future spacecraft programs, arguing against a relaxation of JPL D-1489 redundancy requirements, in most instances, at least for selected subsystems. Other groupings of anomalies led to recommendations for more intensive screening or modified ground testing in certain instances, and an increased emphasis on understanding the underlying physics of failure in all pre-flight, ground-test failures prior to launch. "Physics of failure" is suggested as an improved way of redirecting Product Assurance analyses and conveying prior space flight experience to the new generation of design and Mission Assurance engineers.

REFERENCES:

(1) JPL D-11382 "Development of a Method for Flight Anomaly Characterization", Arthur F. Brown, January 1994.

(2) TETA TO-0024 "Relationship of Test Program History to Flight History - Voyager and Magellan Radio Frequency Subsystem", Charles C. Gonzalez, August 1994.

(3) JPL IOM 3391-93-95, "JPL Previous Mission Telecom Failure History", J. Meeker, November 1993.

(4) JPL Document, "The Galileo High Gain Antenna Deployment Anomaly", Michael R. Johnson, undated.

(5) JPL Document, "Uplink/Downlink JPL Flight Data Analysis," Milena Krasich, September 1994.

I. INTRODUCTION

Background:

NASA Unmanned Flight Anomaly Reports document a series of investigations funded under NASA RTOP 623-63-02, entitled *Flight Anomaly Characterization (FAC)*. The FAC subtask is part of the *Product Assurance Performance Assessment (PAPA)*, a study of ways to improve product assurance processes based on historical experience. The FAC and PAPA are being performed by the Reliability Engineering Section at the Jet Propulsion Laboratory, Pasadena, CA. Under funding provided by NASA Code QT, a database of in-flight hardware anomalies called the Payload Flight Anomaly Database (PFAD) was developed and is being maintained to support FAC and PAPA studies. The PFAD database and associated software possess capabilities for screening anomaly data and generating certain high-level statistics from that data.

Scope:

This report is part of a planned series of NASA Unmanned Flight Anomaly Reports. It presents the findings of an analysis of in-flight hardware anomalies which affected the telecommunications uplink/downlink process on JPL spacecraft, causing at least a temporary loss or significant degradation of signal or essential data. The investigation is limited to the Viking, Voyager, Galileo and Magellan missions. The study is limited to hardware anomalies to reflect the fundamental charter of the JPL Reliability Engineering Section and to conform to the intent of RTOP 623-63-02. The objective of the analysis is to make recommendations for improving product assurance processes based on in-flight experience.

II. DISCUSSION

Method:

The method used in identifying the uplink/downlink anomalies for analysis is described in reference (1). The method involves the development of two flow diagrams. The first is a diagram showing the data contained in the PFAD about each in-flight anomaly. Anomalies that appear to be related are marked for subsequent analysis. A second diagram is then created, combining related anomalies into a single group for more intensive analysis. A separate diagram is prepared for each proposed characterization of the data. Analysis is performed on these diagrams to determine if the proposed correlation is valid or not, and to assess the implications this might have for future product assurance programs.

Data Analysis:

Based on the initial flow diagram developed and reported in reference (1), eleven candidate characterizations of the JPL in-flight anomaly data were identified for subsequent analysis.

These are:

(1) RF Subsystem (Uplink/Downlink) Degradation
(2) Environmental Vulnerability (Thermal, Shock/Vibration, Radiation and EMC).
(3) Mechanical Positioning Anomalies
(4) Memory Anomalies
(5) Debris/Contamination Anomalies
(6) Tape Recorder Anomalies
(7) Thermal Sensor (Mis)application
(8) Gyro Anomalies
(9) Pyrotechnic Anomalies
(10) Structural Interferences
(11) Part Application Anomalies

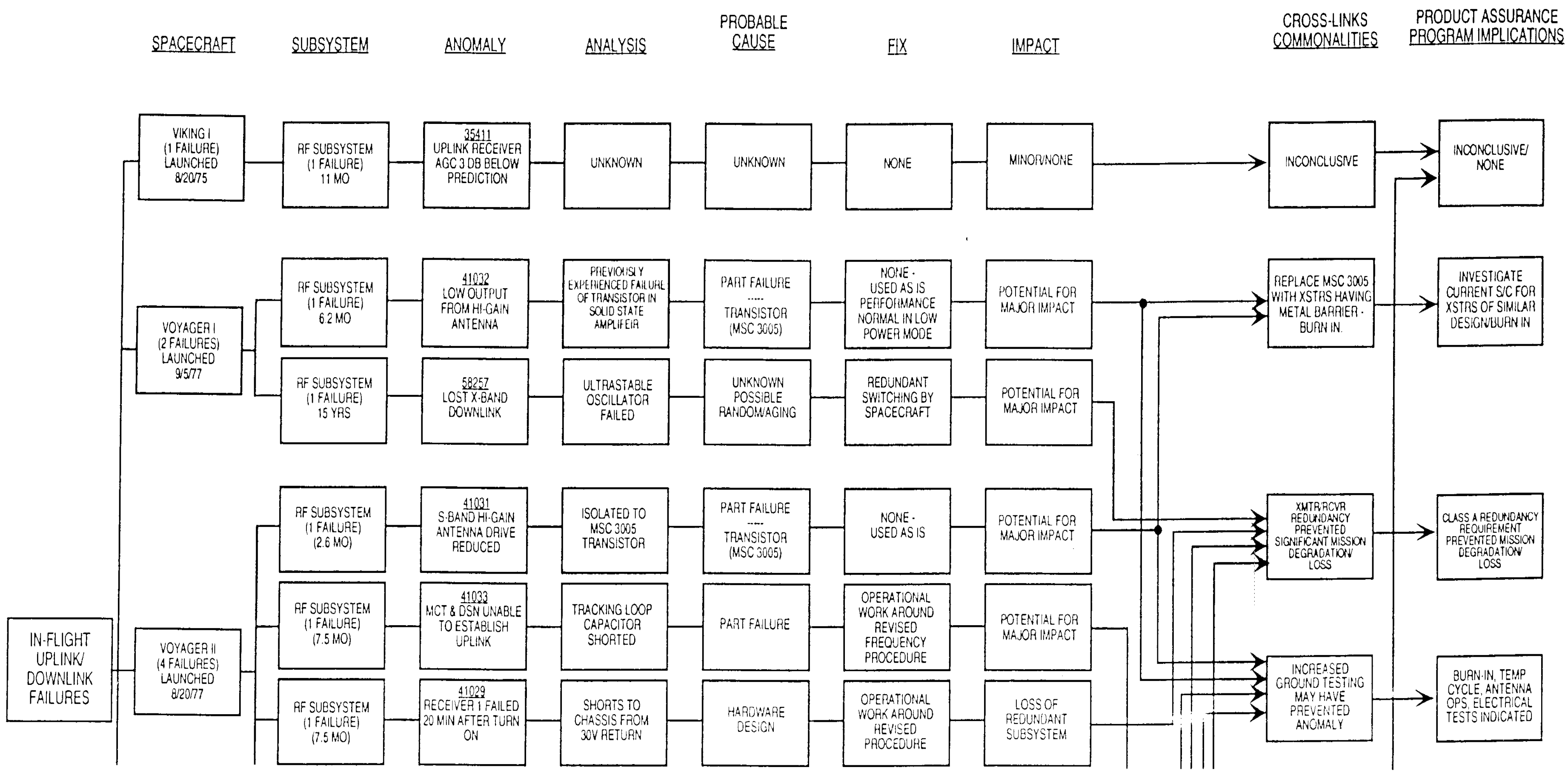
Telemetry anomalies comprise the largest single percentage of the JPL in-flight anomalies investigated. This result was obtained by screening the JPL data for Viking, Voyager, Magellan and Galileo using PFAD and was reported in reference (1). Since some failures in other subsystems also resulted in a loss/degradation of the communication data stream it was decided to include those anomalies also and to generalize the analysis to consider any uplink/downlink anomalies, regardless of the subsystem that failed.

III. RESULTS

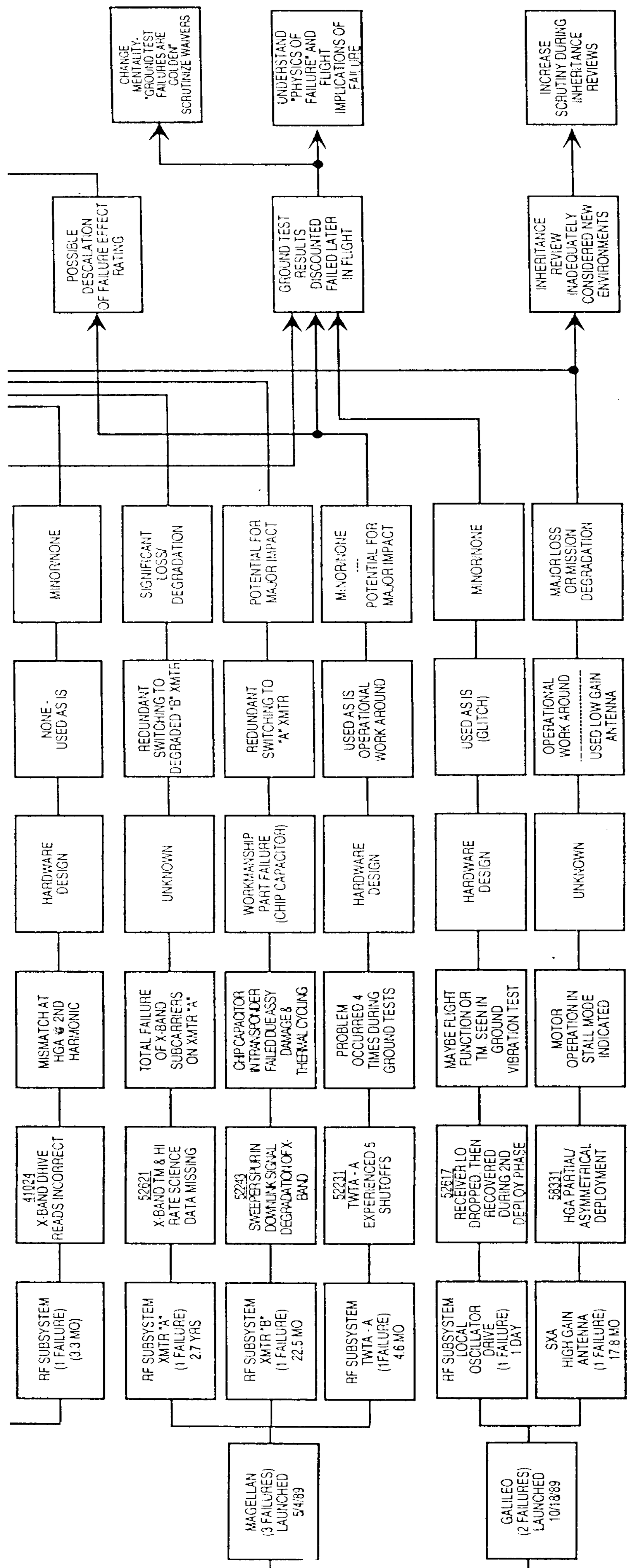
Figure 1 presents a flow diagram of all RF subsystem (RFS) anomalies that interrupted or seriously degraded the uplink/downlink process for the four JPL missions. In order to be included in Figure 1, an anomaly only had to interrupt or seriously degrade an important portion of the communications or science data stream; it did not have to cause complete loss of telecommunications data. Anomalies that appear to share a common "lesson learned" have been grouped as shown in Figure 1. The last column presents proposed ways of applying these "lessons learned" to future product assurance programs. Table 1 presents a summary of product assurance implications, extracted from Figure 1.

Figure 2 presents a similar flow diagram for all non-RFS anomalies that interrupted or seriously degraded the uplink/downlink data stream. Table 2 summarizes the product assurance implications of the analysis of non-RFS anomalies. The combined findings from both diagrams are discussed below.

FIGURE 1


SPACECRAFT
SUBSYSTEM
ANOMALY
ANALYSIS
PROBABLE CAUSE
FIX
IMPACT
CROSS-LINKS COMMONALITIES
PRODUCT ASSURANCE PROGRAM IMPLICATIONS
IN-FLIGHT UPLINK/ DOWNLINK FAILURES
VIKING I (1 FAILURE) LAUNCHED 8/20/75
RF SUBSYSTEM (1 FAILURE) 11 MO
35411 UPLINK RECEIVER AGC 3 DB BELOW PREDICTION
UNKNOWN
UNKNOWN
NONE
MINOR/NONE
INCONCLUSIVE
INCONCLUSIVE/ NONE
VOYAGER I (2 FAILURES) LAUNCHED 9/5/77
RF SUBSYSTEM (1 FAILURE) 6.2 MO
41032 LOW OUTPUT FROM HI-GAIN ANTENNA
PREVIOUSLY EXPERIENCED FAILURE OF TRANSISTOR IN SOLID STATE AMPLIFEIR
PART FAILURE ----- TRANSISTOR (MSC 3005)
NONE - USED AS IS PERFORMANCE NORMAL IN LOW POWER MODE
POTENTIAL FOR MAJOR IMPACT
REPLACE MSC 3005 WITH XSTRS HAVING METAL BARRIER - BURN IN.
INVESTIGATE CURRENT S/C FOR XSTRS OF SIMILAR DESIGN/BURN IN
RF SUBSYSTEM (1 FAILURE) 15 YRS
58257 LOST X-BAND DOWNLINK
ULTRASTABLE OSCILLATOR FAILED
UNKNOWN POSSIBLE RANDOM/AGING
REDUNDANT SWITCHING BY SPACECRAFT
POTENTIAL FOR MAJOR IMPACT
VOYAGER II (4 FAILURES) LAUNCHED 8/20/77
RF SUBSYSTEM (1 FAILURE) (2.6 MO)
41031 S-BAND HI-GAIN ANTENNA DRIVE REDUCED
ISOLATED TO MSC 3005 TRANSISTOR
PART FAILURE ----- TRANSISTOR (MSC 3005)
NONE - USED AS IS
POTENTIAL FOR MAJOR IMPACT
XMTR/RCVR REDUNDANCY PREVENTED SIGNIFICANT MISSION DEGRADATION/ LOSS
CLASS A REDUNDANCY REQUIREMENT PREVENTED MISSION DEGRADATION/ LOSS
RF SUBSYSTEM (1 FAILURE) (7.5 MO)
41033 MCT & DSN UNABLE TO ESTABLISH UPLINK
TRACKING LOOP CAPACITOR SHORTED
PART FAILURE
OPERATIONAL WORK AROUND REVISED FREQUENCY PROCEDURE
POTENTIAL FOR MAJOR IMPACT
RF SUBSYSTEM (1 FAILURE) (7.5 MO)
41029 RECEIVER 1 FAILED 20 MIN AFTER TURN ON
SHORTS TO CHASSIS FROM 30V RETURN
HARDWARE DESIGN
OPERATIONAL WORK AROUND REVISED PROCEDURE
LOSS OF REDUNDANT SUBSYSTEM
INCREASED GROUND TESTING MAY HAVE PREVENTED ANOMALY
BURN-IN, TEMP CYCLE, ANTENNA OPS, ELECTRICAL TESTS INDICATED

The bottom of Figure 1 is continued on this page



RF SUBSYSTEM DEGRADATION ANOMALIES - JPL DATABASE

Table 1 **RF Subsystem Degradation Anomalies**

Finding/ Grouping	Total Anomalies - Percent	P/FR Number	Mission Impact	Programs	Product Assurance Program Implications
Part failure. MSC 3005 RF Power Amplifier transistor failed, causing low output from hi-gain antenna on both Voyagers. At the time, a recommendation was made to use only RF power transistors with a metallic emitter barrier and to increase the burn-in schedule.	2 - 2.4%	41031 41032	PM PM	Voyager 2 Voyager 1	MSC 3005 transistors are no longer used on JPL programs, and burn-in is standard procedure. Ensure that RF power transistors used on future spacecraft have metal emitter barriers and are adequately burned in.
Transmitter/Receiver redundancy prevented total mission loss or significant mission degradation.	4 - 4.9%	41029 58257 52621 58331	LRS PM M M	Voyager 2 Voyager 1 Magellan Galileo	The Class A redundancy requirement in JPL D-1489 has prevented loss of the communication link due to RF Subsystem failures on four JPL spacecraft, both Voyagers, Magellan and Galileo. Relaxation of this requirement on future programs will substantially increase risk.
Increased ground testing could have prevented an in-flight anomaly.	4 - 4.9%	41031 41024 41032 52243	PM N PM PM	Voyager 2 Voyager 2 Voyager 1 Magellan	Specific tests that may have eliminated an in-flight failure were: RF power transistor burn-in (2 failures) VSWR tests of X-band drive (1 failure) Thermal cycling of hybrid circuits (1 failure)
Results inconclusive	1	35411	N	Viking 1	None. Too little data to draw conclusions.

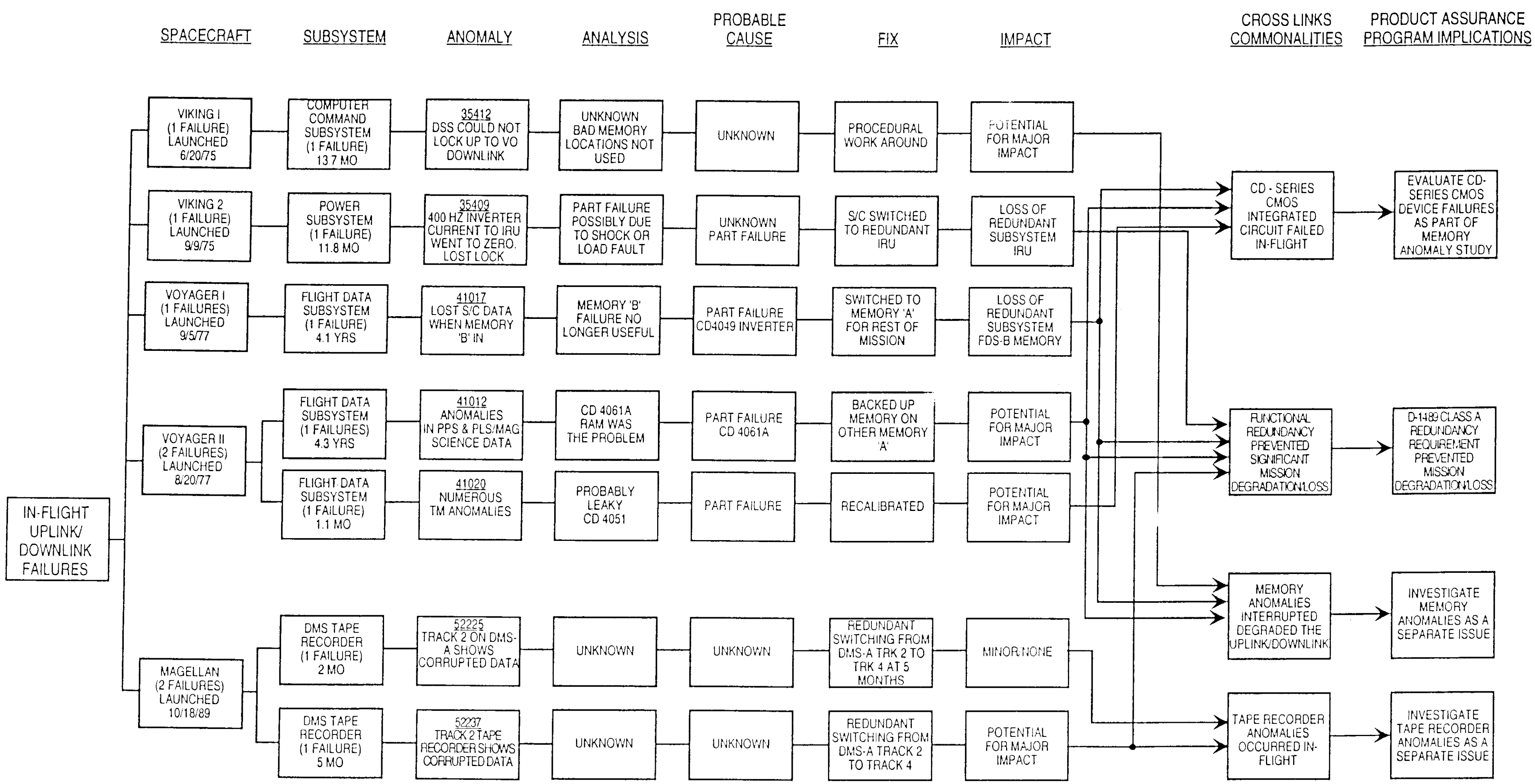
Legend: **N = Minor/No Impact** **PM = Potential for Major/Significant Loss**
M = Major Impact **LRS = Loss of Redundant Subsystem**

Table 1 (Continued) **RF Subsystem Anomalies**

Finding/ Grouping	Total Anomalies - Percent	P/FR Number	Mission Impact	Programs	Product Assurance Program Implications
Ground test failures occurred and then occurred again in flight.	3 - 3.6	52231 52617	N N	Magellan Galileo	In both of these cases, a temporary drop-out had occurred during ground test but the system recovered. The underlying physical reasons for the drop-out and restart were imperfectly understood, but the consequences of a similar failure in-flight were accurately predicted as recoverable.
		41033	PM	Voyager 2	In this case Voyager 1 was flown with a known bad polycarbonate capacitor type; the same capacitor nearly caused catas-trophic mission loss on Voyager 2. A new *"Ground Test Failures Are Golden"* mentality should be adopted. "Physics of Failure" and implications of flight failure must be understood before risk can be accepted.
Inheritance review inadequately considered new and unique environments. Fault tree analysis failed to consider some of the underlying failure mechanisms that were later thought to have produced the in-flight failure.	1 - 1.2%	58331	M	Galileo	Increase scrutiny during inheritance reviews to ensure that *all* environmental differences are considered. Be especially careful when *"minor"* changes are made to the mission profile. Add another level of review to the fault tree process which considers the *"physics of failure"* for observed failure modes and the likely effect of the mission profile on each failure mode.

Legend: **N = Minor/No Impact** **PM = Potential for Major/Significant Loss**
M = Major Impact **LRS = Loss of Redundant Subsystem**

FIGURE 2



NON-RFS UPLINK/DOWNLINK ANOMALIES - JPL DATABASE

Table 2 **Non-RFS Uplink/Downlink Anomalies**

Finding/ Grouping	Total Anomalies - Percent	P/FR Number	Mission Impact	Programs/ Subsystem	Product Assurance Program Implications
Subsystem redundancy prevented significant mission degradation/loss.	5 - 6.1%	35409 35412 41017 41012 52237	LRS PM LRS PM PM	Viking 2/PWR Viking 1/CCS Voyager 1/FDS Voyager 2/FDS Magellan/DMS	Class A redundancy requirement prevented significant mission degradation/loss.
Memory anomalies interrupted/degraded the uplink/downlink.	3 - 3.6	35412 41017 41012	PM LRS PM	Viking 1/CCS Voyager 1/FDS Voyager 2/FDS	Investigate memory anomalies as a separate issue.
CD-series CMOS integrated circuit failed in-flight.	3 - 3.6	41017 41012 41020	LRS PM PM	Voyager 1/FDS Voyager 2/FDS Voyager 2/FDS	Evaluate CD-series CMOS device failures as a separate issue as part of the memory anomaly study.
Tape recorder anomalies affecting uplink/downlink data occurred in flight.	2 - 2.4	52225 52237	N PM	Magellan/DMS Magellan/DMS	Investigate tape recorder anomalies as a separate issue.

Legend: **N = Minor/No Impact** **PM = Potential for Major/Significant Loss**
M = Major Impact **LRS = Loss of Redundant Subsystem**

Subsystem Redundancy

One significant finding of this investigation was that subsystem redundancy saved five of the six JPL spacecraft studied, from a failure of the uplink and/or downlink ranked as catastrophic. On Voyager 1, Voyager 2 and Magellan, redundancy salvaged the uplink/downlink more than once on the same spacecraft. Table 3 lists the eight catastrophic failures. "Catastrophic", as it is used here, means a loss of uplink and/or downlink communications or a significant loss of science data. "Redundancy", as it is used here, means that another subsystem, capable of performing the same or an equivalent function was available on board the spacecraft. The table also lists two non-catastrophic failures (Viking 1 P/FR 35412 and Magellan P/FR 52243) which interrupted or seriously degraded the downlink signals. In the Magellan anomaly, at 22.5 months, Transmitter B produced degraded data and was switched out in favor of Transmitter A. Degraded Transmitter B was switched back in eight months later when Transmitter A failed completely. Even though both transmitters failed, only the Transmitter A failure was counted as being catastrophic and salvaged by redundancy.

In the Viking 1 anomaly, at 13.7 months, the DSN could not lock up with the Viking Orbiter downlink signal. The problem resulted from five bad locations in the Command Control Subsystem (CCS) 'B' memory. At the time of the failure, the 'B' memory stored only the error correction routines; all other spacecraft functions were running on the 'A' memory. A memory location in 'B' memory that set the maximum allowable time the spacecraft would wait without receiving a sun reference went from a ONE to a ZERO. When the spacecraft went through a sun occultation, the error in the timing reference caused the spacecraft to prematurely initiate a sun-loss routine. It switched to the low gain antenna (LGA) and reduced the data rate. The DSN which was expecting a higher signal level and data rate lost acquisition. A work-around was developed by not using the faulty memory locations and the 'B' memory subsequently worked successfully. Surplus memory capacity (minimal) was shown to be necessary, but redundant memory was not. The anomaly was listed as non-catastrophic.

Viking, Voyager and Magellan, were all considered eminently successful missions, but would have experienced significant failures had redundancy not been built into the hardware. In the current funding environment, there is strong pressure for cost reductions on programs and there is an increasing tendency toward less-than-Class A programs. Class A is the only mission class in JPL D-1489 that requires redundancy of essential functions. To quote the Class A requirement:

> "Success-critical single failure points (SFP) are not permitted if avoidable by functional or block redundancy. Unavoidable single failure points must have a Category B project waiver with justification based on risk analysis and measures implemented to minimize risk."

Table 3 **JPL In-flight Anomalies that were Resolved via Redundancy**

PFR No.	Spacecraft/ Subsystem	Time of Failure	Description	Cause	Impact	Immediate Fix	Catastrophic Loss?
52237	Voyager 2/ DMS Tape Recorder	5 months	Track 2 tape recorder shows corrupted data	Unknown	Potential for ma or impact	Redundant switching from DMS-A track 2 to track 4	Yes
41029	Voyager 2/ RFS	7.5 months	Receiver 1 failed 20 minutes after turn-on	Hardware design, shorts to chassis from 30v return	Loss of redundant subsystem	Operational work-around revised procedure	Yes
35409	Viking 2/ PWR	11.8 months	400 Hz Inverter current to IRU went to zero. Lost downlink	Unknown part failure	Loss of redundant subsystem	System switched to alternate gyro	Yes
35412	Viking I/CCS	13.7 Months	DSS could not lock up to VO downlink	Unknown, memory problem	Potential for ma or impact	Bad memory locations were not used	No
58331	Galileo/SXA High Gain Antenna	17.8 months	HGA partial/asymmetrical deployment	Unknown	Ma or loss or mission degradation	Used low gain antenna, reconfigured mission	Yes
52243	Magellan/ RFS XMTR B	22.5 months	Sweeper spur in downlink signal. Degradation of X-band	Workmanship, part failure (chip capacitor)	Potential for ma or impact	Redundant switching to XMTR A	No
52621	Magellan/ RFS XMTR A	2.7 years	Total failure of X-band subcarriers on XMTR A	Unknown	Significant loss/ degradation	Redundant switching to XMTR B	Yes
41017	Voyager 1/ FDS	4.1 years	Lost spacecraft data when memory 'B' in	Part failure - CD4049 inverter	Loss of redundant FDS 'B' memory	Switched to memory A for rest of mission	Yes
41012	Voyager 2/ FDS	4.3 years	Anomalies in PPS and PLS/ Mag science data	Part failure - probably leaky CD4051	Potential for ma or impact	Backed up memory on other memory 'A'	No
58257	Voyager 1/ RFS	15 years	Lost X-band downlink	Unknown, ultrastable oscil-lator failed	Potential for ma or impact	Redundant switching by spacecraft	Yes

The flight history on earlier programs must be kept in mind when considering relaxation of this requirement for critical functions, such as the telecommunications link. The evidence confirms that there is a significant probability that a spacecraft with single-channel communications will experience a significant failure of the telecommunications process.

Estimating the Probability of Success

Quantifying this probability from such limited data provides little statistical confidence, but the data can give a certain "engineering feel" which might influence future decisions about spacecraft redundancy. Based on the data from the six JPL spacecraft studied, Table 3 shows eight failures which would have been catastrophic, except for redundancy. If only the RFS failures are considered, four failures would have effectively disabled Voyagers 1 and 2, Magellan and Galileo. Assuming that each of the six spacecraft had simple dual channel redundancy of critical functions, Milena Krasich calculated the probability of success for a single-channel system as a function of time from launch. The first plot is for RFS failures only and the second is for all catastrophic failures that interrupted the uplink or downlink data stream. These results are shown in Figures 3 and 4. A Weibull distribution (decreasing failure rate) was found to fit the data better than an exponential distribution (constant failure rate), and the figures assume the Weibull. The three curves in each figure give the 90% upper and lower confidence limits on the point estimate of the shape parameter β. Her calculations are reported in reference (5).

It should be pointed out that these figures are based on very limited failure data and include only data stream and telecommunications failures. Inclusion of catastrophic failures (if they exist) in critical subsystems which are not associated with the uplink/downlink process will further reduce the estimate of mission success probability. The figures should be used cautiously, and supplemented with other data if available. Reference (3) reports data on earlier JPL programs which experienced substantially fewer telecommunications failures. Nevertheless, the data reported here represent the most recent twenty years of JPL flight history on Class A missions, and should certainly bear heavily on future decisions about telecommunications redundancy.

The principle which enabled so many JPL missions to be successful in spite of numerous in-flight failures is simply the large improvement in reliability that results when a functionally equivalent redundant subsystem is added to a single-string system.

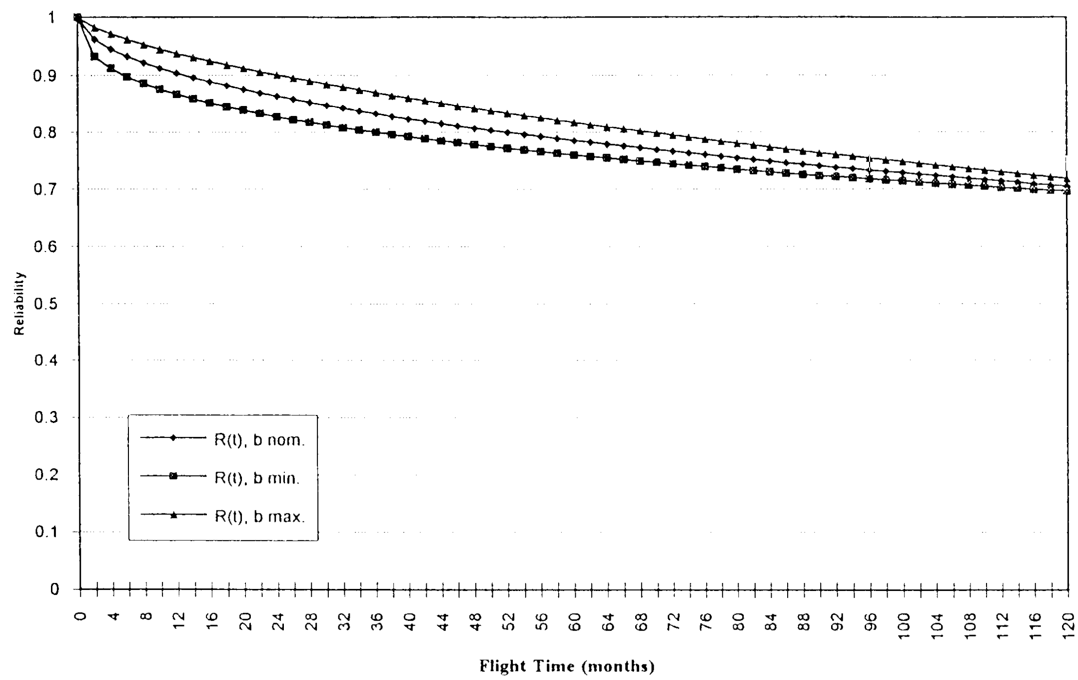


Figure 3
Probability of Success as a Function of Time from Launch in Months - RFS Failures

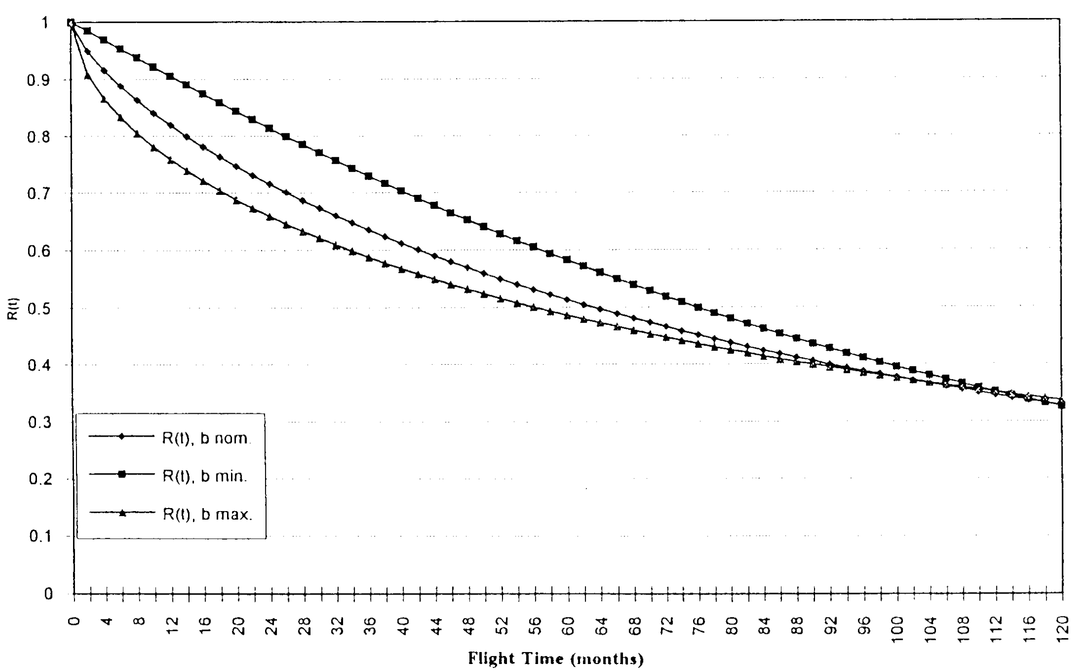


Figure 4
Probability of Success as a Function of Flight Time in Months - All Failures

Additional Ground Testing Implications

Five anomalies were experienced which appeared to be potentially preventable by additional screening or ground tests. This issue was addressed in both references (2) and (4) which investigated the ground tests performed on Voyager 1, Magellan and Galileo in considerable detail, and those findings are referenced here, as appropriate. Table 4 lists the anomalies. The additional tests fall into four broad categories:

Burn-In of Piece Parts. Failure of the MSC 3005 r.f. power transistor, manufactured by Microwave Semiconductor Corporation, was responsible for two Voyager anomalies. One failure occurred on Voyager 2 at 2.6 months and the other on Voyager 1 at 6.7 months after launch. At the time the failure analysis was done, the analysts recommended that the MSC 3005 and similar transistors without a metal emitter barrier not be used on future systems. They also recommended that the transistors be adequately burned-in. Reference (2) states that the failure mechanism was migration of the aluminum emitter contact into the emitter exacerbated by high temperature due to a poor heat sink solder joint.

The issue of the MSC 3005 was discussed with the JPL semiconductor components group, and it was verified that the device is no longer used on any current JPL spacecraft. Adequate burn-in is routinely performed on all space qualified semiconductors, and should not be an issue on modern spacecraft, unless some proposal is made to waive it in an effort to reduce costs.

The issue raised by poor thermal conductivity to the heat sink, either due to a faulty solder joint or some other type of heat sink connection could potentially be resolved by performing a thermal scan on electronic assemblies. The test should be reasonably inexpensive to run and could be combined with other electrical tests. Any devices with poor heat conductivity will rise in temperature above predicted levels during powered operation. The thermal scan would highlight devices with a poor heat sink connection, and steps could be taken to correct the thermal conduction path. The test is undoubtedly cheaper than power-on vibration and should be more effective in finding this kind of failure.

Thermal Cycling of Hybrid Microcircuits. Magellan experienced one in-flight failure of a hybrid microcircuit which the manufacturer attributed to a failed chip capacitor aggravated by damage during assembly. Although non-catastrophic, this was a significant failure, and the transmitter was switched out. Thermal cycling was recommended by the analysts as a way to screen out similar failures.

Thermal cycling has both positive and negative effects, and its use should be considered judiciously on space systems. The advisability of thermal cycling cannot be resolved based on this single failure. Other RTOP activity is currently underway which indicates that the bulk of failures are removed during the first thermal cycle and further temperature cycling may actually induce failures that would not otherwise have occurred during flight.

Resolution of the thermal cycling question will be left to other investigators. For the purposes of the FAC study, any in-flight failures where thermal cycling appears to be a potential solution will be reported to the analysts performing the thermal cycling studies.

Ground Tests of the Galileo HGA. Failure of the Galileo High Gain Antenna (HGA) to deploy when commanded resulted in a nearly catastrophic failure of the Galileo mission. The mission has been about 70% salvaged by using the Low Gain Antenna at much reduced data rates and by introducing data compression techniques. In reference (4), Michael Johnson reports extensive analysis that proves rather conclusively that additional ground testing would not have detected the problem. The analysis finds that the most probable cause of failure was retention of the antenna ribs at the mid-point due to excessive friction, galling or adhesion. The postulated increased friction was caused by a round-end pin in a V-groove socket which produced contact stresses high enough to remove a molybdenum disulfide dry-lubricant coating. In a vacuum environment, aggravated by vibration, the pins developed very high friction in the sockets and could not deploy the antenna. A unique sequence of events which could not have been reproduced during the test program had to occur to induce the failure:

(1) Vibration under atmospheric conditions which accelerated the removal of the MoS_2 coating. This occurred during the several trips to the Cape and during ground tests.

(2) Vibration under vacuum conditions to produce galling of the titanium pins. This occurred during the upper stage burn of the launch system.

If there are messages for the product assurance program in the HGA deployment failure, they are probably these:

(1) There are some failure mechanisms that require a sequence of environments that will probably never be predictable or reproducible during ground tests.

(2) Inheritance of hardware from other space programs can give a false sense of security. There were significant differences in the environment of the Galileo mission and the TDRS program from which the HGA design was inherited. These may have been exacerbated by the VEEGA (Venus-earth-earth-gravity-assist) mission which was added after the antenna had already been selected. VEEGA resulted in a much longer duration under vacuum conditions and increased temperatures over the originally planned mission.

Table 4 **Ground Test Implications**

P/FR No.	Spacecraft	Sub-system	Description	Cause	Impact	Ground Test Implication
41032	Voyager 1	RFS	Low output from High-gain Antenna	Part Failure. -------- Transistor (MSC 3005)	Potential for Ma or Impact	Burn-in power transistors. Eliminate MSC 3005 Transistor.
41031	Voyager 2	RFS	S-Band High-Gain Antenna drive reduced	Part Failure. -------- Transistor (MSC 3005)	Potential for Ma or Impact	Burn-in power transistors. Eliminate MSC 3005 Transistor.
41024	Voyager 2	RFS	X-Band drive reads incorrect	Hardware Design -------- Mismatch at HGA @ 2nd Harmonic	Minor/None	VSWR tests could have found this failure.
52243	Magellan	RFS XMTR B	Sweeper spur in downlink signal. Degradation of X-Band	Workmanship, Part Failure -------- Chip capacitor failed due to assembly damage & thermal cycling.	Potential for Ma or Impact	Thermal cycling of hybrid microcircuits should find this kind of failure.
58331	Galileo	SXA High-gain Antenna	HGA Partial/ Asymmetrical Deployment	Unknown	Ma or Loss or System Degradation	Ground tests of the antenna deployment system would not have found this failure.

(3) Even though spacecraft and missions change, the underlying physics of failure does not. What is needed is a way to record the failure physics that are involved in observed flight failures and convey that information to the new generation of design engineers and reliability analysts so the same errors are not repeated in subsequent missions. In this case, the following advice might be recorded for future spacecraft programs to consider:

"Round pins in V-grooves under continuous pressure create two points of extremely high stress. These have been shown to be capable of removing lubricant coatings, causing galling, high friction, and potentially cold welding. Vibration, vacuum and long-term pressure stress aggravates the friction. Watch for these conditions during design, FMECA and fault tree analyses"

VSWR Tests of High Gain Antenna Drive. Voyager 2 experienced an incorrect drive reading at the High Gain Antenna which was determined by subsequent ground tests to be the result of a mismatch at the second harmonic of the drive frequency. Although this raises the question of why the mismatch was not noticed during pre-launch testing, the impact on the mission was negligible and there was only one in-flight anomaly of this type. The effect appears to be second-order and to have little impact on product assurance issues.

Discounted Ground Test Failures - Magellan and Galileo Anomalies. Two anomalies related to the uplink/ downlink process that occurred in-flight had previously occurred during ground tests, but were discounted as having minor potential effect in-flight. A travelling wave tube amplifier, TWTA-A, on the Magellan spacecraft, experienced 5 shut-offs during flight. In all cases, the TWTA came back on, (but caused operational difficulties.) This same problem had occurred four times during ground tests. On the Galileo spacecraft, Local Oscillator (LO) drive dropped out on one of the receivers after one day of flight. LO drive recovered during the second deployment phase. A similar dropout had occurred during ground vibration tests.

These two results may have a significant implication for future spacecraft programs in which lower cost must be traded against additional risk. Both of the failures were anticipated prior to launch, and a considered judgement was made that the flight risk was acceptable. When similar failures occurred in-flight, they, in fact, had a minor impact (although not insignificant) on the mission, as predicted. The message for future programs is that risks can be taken when glitches occur during ground testing, provided the potential in-flight results are adequately analyzed. Based on the available evidence, the mission result of such decisions in the past, at least for uplink/downlink issues, has been positive, i.e., the spacecraft have flown successfully, even though similar in-flight failures occurred.

Despite the success in these two instances, there is another message for product assurance programs in the TWTA shut-off failure. A change in mentality is needed when ground test failures occur. Every ground test failure must be thoroughly resolved before clearing hardware for launch. Ground test failures should be considered "golden," i.e., the fact that they occurred during ground tests rather than in-flight is a piece of good fortune. Understanding and fixing them will never be easier or cheaper. There can be a desire, because of launch schedules or cost constraints, to attempt to find a "quick fix". In these two cases, a determination was made that a similar failure in-flight would have only a minor impact and the hardware could be flown. So long as the TWTA or LO came back on, the effect would, at worst, be a temporary loss of data. The potential flaw in such arguments is that until the underlying failure mechanism is understood, there is no assurance that the next failure will be "similar", i.e., that the TWTA or LO will necessarily restart.

In these instances, there was always a second channel that could be brought into service if the first one failed. As single channel systems become more the norm, the need to identify and fully understand the underlying physics of failure involved in ground test failures becomes much more critical. If Magellan had been a single-channel system, and the TWTA had not come back on, the result would have been a catastrophic mission loss.

Discounted Ground Test Failures - Voyager 2 Anomaly

At 7.5 months, the Deep Space Network (DSN) was unable to establish an uplink with Voyager 2. The failure was attributed to a shorted tracking loop capacitor which caused a shift in the receiver center frequency. The redundant S-band receiver was cycled in and failed catastrophically 20 minutes after turn-on due to an unrelated ground short. A workaround for the first receiver failure was found by transmitting the uplink signal at a new frequency, accommodating the center frequency shift including temperature and doppler corrections due to spacecraft motion.

In reference (2), Charles Gonzalez summarized the findings of ground tests related to this capacitor failure. The capacitor series, a PT 40452-031 polycarbonate manufactured by Dearborn, exhibited similar failures during ambient fabrication/ assembly testing of the Voyager proof test module (PTM) and again during ambient testing at the Kennedy Space Flight Center. The capacitors are prone to dielectric punctures which are self-healing in high voltage circuits. Its use in a high impedance, low voltage circuit seems a questionable application of the part, and the ground test failures certainly gave adequate warning of a possible part misapplication. The failure mechanism was postulated to be micron-sized particles imbedded in the dielectric that cold-flowed to cause short circuits. Voyager 1 was flown despite the known failure mechanism primarily for schedule reasons. Again, the decision worked out positively because no such failure occurred on Voyager 1. However, the presence of dual receivers was undoubtedly a significant factor in the decision to launch Voyager 1. Considering the catastrophic failure of the other receiver on Voyager 2, the capacitor failure came very close to scrubbing the Voyager 2 mission. Again, this points out how much more critical it is to understand the underlying physics of any ground test failure for the single channel missions of the future.

De-escalation of Failure Effect Codes

Only one instance was found which suggested a tendency toward de-escalating failure effect codes.

This was the previously mentioned group of five spurious TWTA shut-offs that occurred on the Magellan spacecraft. This P/FR (52231) was assigned a Failure Effect code of 1 (negligible or insignificant effect) and a Failure Risk code of 3 (known cause/uncertain fix, some residual risk). Any failure of the TWTA interrupted the downlink, at least momentarily, and depending on when that happened and how long it persisted, it could have had a catastrophic impact. From the limited data in PFAD, it isn't clear whether the interruptions were momentary or prolonged. TWTAs that shut off probably restart on random noise, making the restart somewhat unpredictable. Nevertheless, the FR code of 3 implies that the risk associated with the fix (presumably waiting for the TWTA to restart) was not well understood. It seems that the FE rating of 1, is more the result of chance (i.e., by chance, the failures did not have a significant effect on the mission), rather than providing any assurance that TWTA shut-off would be insignificant under other conditions.

Based on this single instance, nothing definite can be said about any tendency to reduce the failure effect rating in P/FRs. There are obviously programmatic and career pressures that might make an individual want to do it. This is an issue which will be watched on subsequent FAC characterizations of the anomaly data, and if a pattern develops, it will be reported.

Memory Anomalies/CMOS Integrated Circuits

Three memory anomalies on Viking and Voyager either interrupted or degraded the uplink/downlink process. Memory anomalies have already been identified in reference (1) as a characterization of the data that deserves independent FAC analysis. Two of the memory anomalies and another anomaly were due to CD-series CMOS integrated circuit-failures. CD-series integrated circuit failures will be considered as a special subset in the investigation of memory anomalies.

Inconclusive Characterizations

In addition to the failures in Tables 1 and 2 which can be combined and characterized, one anomaly did not lead to any clear conclusion. Viking 1 experienced an unexplained 3dB loss in Receiver AGC gain after eleven months of operation. This anomaly had a minor effect on the mission, but was not successfully explained.

IV. CONCLUSIONS

Redundancy of Critical Functions

The most significant finding of this study was the fact that five of the six JPL spacecraft studied would have experienced a catastrophic failure of the uplink and/ or downlink, except for designed-in redundancy. All of the spacecraft studied were Class A programs subject to the requirement that no single-point failures of critical functions are permitted. All of the programs were considered successful, some for example, the two Voyagers, successful beyond all expectations. In this present era of mission downsizing and reduced budgets for space programs, there is substantial pressure to use less-than-Class A requirements for new systems. It is sobering to note that all but one of the major JPL programs in the past twenty years would have experienced a catastrophic failure of the uplink/downlink except for the Class A redundancy requirement. This result has a significant implication for future space missions and their product assurance programs. Based on prior history, the D-1489 redundancy requirement for all critical functions of the telecommunications uplink and downlink should not be relaxed. Considering the high expected probability of failure shown in figures (3) and (4), the result also applies to many non-Class A missions.

Understanding the "Physics of Failure"

All three of the instances of ground test failures which later occurred in flight point up the need for thorough understanding of the physics of failure involved. Only when the underlying physics is known can accurate predictions be made of what the likely in-flight experience will be. In order to assess the risk of launching without correcting the failure, repeatability of the failure must be certain, and the in-flight effects must be fully understood to make sure the mission impact will be acceptable. This becomes much more important when single-string missions are flown to reduce costs. Situations will undoubtedly arise in which a redundant spacecraft could be launched without correcting a ground-test failure, but the risk to a single-string mission will be unacceptable.

There are other advantages to concentrating on "physics of failure." This is probably the easiest way to teach new spacecraft designers. Spacecraft and missions change dramatically; failure physics does not. As an example, the fault tree analysis done on the Galileo HGA did not consider the failure mechanisms that were later shown to be the cause of the deployment failure. There is no guarantee that an analyst would have predicted the HGA failure, however, once it has happened, those physical conditions that caused it should become part of the "corporate memory," and all future spacecraft should be analyzed with that in mind.

V. RECOMMENDATIONS

The principal recommendations for product assurance programs resulting from this investigation are:

(1) Review requests for waiver of the D-1489 redundancy requirement for uplink/downlink functions very judiciously, recognizing that recent JPL history predicts a high probability of failure for longer missions if redundancy is not provided. The charts shown in figures 3 and 4 may be helpful in estimating the probability of success as a function of mission length.

(2) Avoid the use of r.f. power transistors without a protective metallic emitter barrier. Ensure that burn-in is being performed on all power semiconductors.

(3) Make sure that the underlying physics of failure are understood when reviewing ground test failures before a spacecraft is released for flight. Unresolved ground test failures can reoccur in flight, and unless the failure mechanisms are fully understood, the results of the in-flight failures cannot be predicted. Ground test failures should

be considered "golden." They provide an opportunity to understand and fix the failure at minimum programmatic cost.

(4) Consider a thermal scan in conjunction with electrical tests to locate "hot spots" that are indicative of power devices with poor thermal conductivity to the heat sink. The test should be easy and inexpensive to run and more effective than power-on vibration in locating poor thermal connections.

Further analysis is required on several findings of this study:

(1) Support the investigation of thermal cycling as a means of screening out potential in-flight failures in conjunction with the Environmental Test Effectiveness Analysis (ETEA) subtask of the PAPA.

(2) Consider the issue of possible inappropriately assigned Failure Effect codes in other characterizations of in-flight anomalies to see if a pattern emerges.

(3) Add CD-series CMOS integrated circuit failures as a subset of the memory anomaly characterization for future study.

(4) Develop a check list of anecdotal data based on JPL in-flight failures that can be used in training new design engineers and reliability analysts. This check list should emphasize the "physics of failure" associated with the in-flight anomalies.